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13. ABSTRACT (Maximum 200 words)

The objectives of this work have been to develop methods for extracting quantitative information from the Reflection High Energy Electron Diffraction (RHEED) pattern about the surface structure of nearly perfect crystals prepared by Molecular Beam Epitaxy (MBE) and to use these techniques to explore in detail the growth of homo-and heteroepitaxial structures involving GaAs, AlAs, InAs, and related ternary compounds. The overall problem addressed is the development of highly controlled growth of multilayers, quantum wells, delta doping, Bragg reflectors, and other structures which can then be exploited in advanced electronic and photonic devices.

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A. Statement of the Problem Studied

The objectives of this work have been to develop methods for extracting quantitative information from the Reflection High Energy Electron Diffraction (RHEED) pattern about the surface structure of nearly perfect crystals prepared by Molecular Beam Epitaxy (MBE) and to use these techniques to explore in detail the growth of homo-and heteroepitaxial structures involving GaAs, AlAs, InAs, and related temary compounds. The overall problem addressed is the development of highly controlled growth of multilayers, quantum wells, delta doping, Bragg reflectors, and other structures which can then be exploited in advanced electronic and photonic devices.

B. Summary of the Most Important Results

The thrust of the research has been to develop better control of MBE growth using enhanced RHEED measurements and to use the resulting control to grow advanced heterostructures for electronic and optoelectronic applications. This research has been very productive, resulting in 22 articles published or submitted. Three MS and three PhD students have completed their degrees under this ARO sponsorship. A brief summary of this research follows:

RHEED Studies and MBE System Enhancements

Enhancements to our RHEED system, including computer access of the pattern with a CCD camera and image processing system, allow us to look in detail at the intensities across the specular streak of the RHEED pattern during MBE growth of GaAs. We found that during the growth of a single monolayer, intensities of structure within the principal streak oscillate with the period of the main line, but in some cases are out of phase. We identified these features with the effects of Kikuchi scattering during the growth of a monolayer of single crystal material on the surface.

We have had considerable success in studying surface roughening during MBE growth, using a combination of RHEED and photoluminescence studies of quantum wells. Since transitions involving discrete states in quantum wells have characteristic transitions depending on well width, we have used PL on samples with several wells of different widths to study the details of layer thickness. For example, by growing a series of wells of integer monolayer thickness we can examine the transition energies for the series of wells. If we grow intermediate wells using growth times which would result in half-monolayer changes in width, we find corresponding intermediate transition energies (apparently corresponding to an average of the resulting microroughness). Interestingly, when the experiment of 3, 3.5, 4, 4.5 ... well widths is repeated using 60s growth interruption at each layer, we observe only the transitions characteristic of integer monolayer widths (3, 4, 5,....monolayers). Apparently the microroughness incorporated in the n + 1/2 monolayer wells is smoothed out during the interruption. It appears clear that the combination of RHEED and PL on QWs is a useful way of studying layer roughness, and that smoothing during growth interruption can be studied this way.

We have intentionally introduced AsO during the growth of GaAs and AlGaAs to study its effects on the dampening of RHEED oscillations and the photoluminescence of quantum well (QW) structures. The AsO (as determined by a mass 91 peak in the residual gas analysis of the beam) was obtained from the cracking section of our As dimer cell prior to the baking of the source. This allowed us to introduce a controlled amount of AsO proportional to the cracker temperature. The AsO was found to affect both the RHEED and the photoluminescence. We

found that the dampening of the AlGaAs increased with increasing AsO concentrations. Little effect was found upon the dampening of the GaAs. Following the RHEED studies for each set of growth parameters, a set of four QWs were grown with GaAs well thicknesses of 5, 11, 19, and 35 monolayer separated by 500 Å barriers of $Al_{0.3}Ga_{0.7}As$. The presence of AsO was found to have a dramatic effect on both the integrated intensity and the linewidth of the photoluminescence spectra for QW samples. The cracking section of the As source was then baked until the 91 peak was greatly reduced (with the cryogenic panels cooled there was no detectable AsO in the system) and the experiments were repeated. The RHEED dampening became essentially independent of the temperature of the cracking section. The photoluminescence of the QW layers was also dramatically improved, but still displayed a trend of lower integrated intensity and larger linewidths as the cracking section temperature was increased. Photoluminescence of QWs is thus a more sensitive measure of the presence of AsO.

To further improve the control of growth in our Varian Gen II MBE system, we have developed under State of Texas support new thermal effusion cells designed to reduce the "Ga spitting" problem and a unique As dimer source using an all-metal sublimator/cracker system. The use of the As cracker not only allows us much better control of As flux, but also allowed us to grow for 10 months in a recent period without opening the system.

Precise Growth of Multilayers

One of the most stringent applications of precise growth of multilayers is in resonant tunneling structures, for which single-monolayer accuracy in well and barrier widths is important. Our studies have centered on a device invented and developed in our laboratory, called the Quantum Well Injection Transit Time (QWITT) diode. We are able to grow tunneling structures with excellent peak to valley ratios and other resonant tunneling properties. Using DLTS and I-V studies, we determined early in this research that previous studies which suggested a temperature of 560 °C or lower is necessary to prevent degradation of the quantum well structure are incorrect. We demonstrated that growth at 650 °C results in excellent resonant tunneling structures, while avoiding the interface defects common in structures grown at lower temperatures.

Another important test structure for precise growth is modulation-doped and delta-doped quantum wells. We have examined these structures in considerable detail, in both lattice matched and pseudomorphic materials. We studied the relationship between photoluminescence spectra and the electrical properties of modulation-doped AlGaAs/GaAs and pseudomorphic InGaAs/GaAs quantum wells (MDQWs). We have also used electron beam electroreflectance (EBER) techniques in collaboration with Charles Evans and Associates to study these structures. We have been able to correlate PL linewidth with the presence of a large sheet carrier density in the quantum well, and have shown the ratio of 77K to 4.2K PL linewidths to be a useful measure of the crystalline quality of these quantum well structures.

We have found that short-time heating, which is often necessary in device processing, causes changes in the electrical and optical properties of MDQWs. Close-contact annealing results in a decrease in carrier density with annealing, owing to Si auto-compensation in the doped AlGaAs. For anneal times ≥ 40 s at 900°C, the mobility also decreases. Optical evidence suggests that the primary mobility degradation mechanism is Si diffusion, which reduces the effective spacer thickness. RTA also degrades the interface, resulting in more extrinsic PL transitions and wavevector non-conservation. The 2-DEG carrier density, 4.2 K Fermi energy and 77 K PL linewidth closely track the variation of carrier density with annealing, indicating that monitoring these parameters facilitates the non-destructive optical characterization of MDQWs. An average Si diffusion coefficient of 3.5×10^{-14} cm^2/s at 900°C was deduced from PL spectra.

The delta doping technique, which ideally confines dopants into a plane, exhibits two-dimensional carrier concentrations higher than 10^{13} cm^{-2}, an order of magnitude higher than that of conventional uniform doping. This also results in enhanced carrier mobilities due to strong screening of scattering centers. We have found a strong narrowing effect on the C-V carrier profiles of delta-doped quantum wells, since electrons are not only confined by the delta-doping but also by the quantum well. Using test structures of Si delta-doped $Al_{.3}Ga_{.7}As/GaAs$ quantum wells with various well thicknesses, we observed a C-V FWHM width varying from 27Å for a 50Å QW to 39Å for a 150Å QW, and more than 100Å FWHM for a similar delta doping in bulk GaAs. All layers were grown to have similar annealing times, to avoid changes due to diffusion.

Defect Studies

We have used both low-temperature photoluminescence and DLTS studies to examine defects in MBE-grown material. For example, in the study mentioned above regarding the growth temperature appropriate for QW tunneling structures, we found with DLTS that defects introduced at the lower growth temperatures can severely affect the QW structures. In particular, we found a dramatic impedance switching effect in structures grown at 550 °C, due to the presence of a high concentration of deep levels. In our DLTS studies we examined the DX center in AlGaAs, and found that the time and temperature behavior of its capture and emission characteristics can be modelled using a Williams-Watts stretched exponential decay analysis.

Low Temperature Growth of GaAs and AlGaAs

We have studied the low temperature (250°C -300°C) growth of undoped GaAs and $Al_{0.3}Ga_{0.7}As$ layers for high resistivity buffer and gate insulator applications. As a tool for studying such insulating layers, we have made MIS structures using these layers as the insulator in C-V and I-V measurements. We demonstrated that both the binary and ternary can be grown successfully at these low temperatures, and that a twenty minute annealing step in an As environment is important in the formation of highly resistive material. The unannealed material displays a high concentration of deep levels in DLTS, and subsequent carrier freezeout at 77K. On the other hand, we are finding that layers annealed at normal growth temperatures (600 °C) can be of quite good quality, while maintaining or increasing their insulating properties.

In addition to basic materials studies of the low temperature grown (LTG) layers by DLTS, resistivity, etc., we have begun to examine whether good device-quality layers can be grown on top of the semi-insulating LTG material. Two approaches we have taken are to grow quantum wells for PL and other measurements, and to make some defect-sensitive devices such as solar cells.

To evaluate the quality of subsequently grown epitaxial layers, quantum wells were grown on top of the LTG buffer layer. As a first experiment, quantum well (AlGaAs/GaAs/AlGaAs) structures were grown on top of a fixed thickness of LTG GaAs grown at 300 °C. A layer of regular GaAs was grown at 620 °C between the buffer and the QW. The integrated intensities when plotted as a function of distance were fairly constant, which is very encouraging. We also varied the thickness of the low temperature GaAs and kept all other parameters constant. The photoluminescence line widths (FWHM) of all the wells were 1.4 - 2.1 meV. The integrated intensity showed a sharp increase (by a factor of 2) when there was no low temperature buffer, but was almost constant with increasing thickness of the low temperature buffer.

These experiments indicate that defects in the low temperature buffer do not migrate into epitaxial layers grown on top of the buffer. The integrated intensities from QW structures on top

of the low temperature buffer were almost constant and comparable to that of regular QW structures. We are currently studying the dependence on the growth temperature for the LTG GaAs. The electrical properties (Hall mobility) of epitaxial layers grown on the LTG buffer material is also being checked with inverted HEMT structures.

The performance of minority carrier devices on top of low temperature buffer material is the critical test of this material. We have made solar cells on top of LTG GaAs grown at 270 °C with a conversion efficiency for the first cell of 5.4%. This low efficiency is attributed to high series resistance by the n contact layer. We are currently working with Prof. Joe Campbell on our faculty to improve this cell. In the future we will also be able to use such collaborations with Campbell, Prof. Dennis Deppe, and others in our group to try out a variety of applications in optoelectronics to supplement the obvious applications in FET-type devices. For example, we should be able to use these layers to direct current to the active regions of Deppe's vertical cavity surface-emitting lasers. We are already working with Deppe on other aspects of semiconductor lasers. Combined with our work on understanding the materials aspects of these layers, this type of device application study should be very interesting.

MBE Growth of Vertical Cavity Surface-emitting Lasers

Our work under this ARO contract on the control of MBE growth has enhanced our ability to grow accurately controlled quantum well structures and multilayer heterojunctions, including distributed Bragg reflectors (DBRs). This control of growth allows us to examine details of optical phenomena in short-cavity lasers. In collaboration with Dennis Deppe in our department, we have studied the effects of cavity length on emission for vertical-cavity quantum well lasers. Our experimental data suggest that the gain mechanism of the QW in a vertical cavity surface-emitting laser (VCSEL) is fundamentally increased over that of the conventional edge-emitting laser. It now appears that this increase is due to the strong interaction between the QW and the closely spaced reflectors of the VCSEL. This change in the QW emission characteristics is apparently due to a direct change in the mode density of the vacuum electromagnetic field, which in turn alters the spontaneous Einstein coefficient, and the spontaneous emission linewidth. Even for a QW placed in a moderately high-Q cavity of $Q \sim 300$, a gain increase of a factor of 10 for fixed carrier densities is to be expected, greatly relaxing the mirror reflectivity required for lasing in the VCSEL. This enhancement can be a major advantage for short-cavity lasers.We have obtained data to support the gain enhancement model by studying the emission characteristics of several InGaAs-GaAs QW structures with closely spaced reflectors of either Ag metal or AlAs-GaAs DBR's. Enhancement/inhibition of greater than 1000 are found for the QW emission for various mirror to QW spacings. Our studies of these structures may lead to a considerably enhanced understanding of the technologically important field of surface-emitting lasers.

We have used MBE regrowth techniques to provide current funnelling into the device active region of the VCSEL. We use an AlAs/GaAs Bragg reflector for the n-side mirror, and a combination of AlAs/GaAs and either $ZnSe/CaF_2$ or Si/SiO_2 quarter-wave dielectric layers for the p-side mirror. We are finding excellent laser performance in terms of threshold current and lasing efficiency. Recently we have discovered a bistability in the I-V and light-V characteristics of a quantum well VCSEL. The bistability apparently stems from impedance change in the laser active region at threshold, and the hysteresis width seems to be controlled by leakage current around the active region. If this bistability turns out to be easily controllable and can be reliably reproduced by growth and processing, it could be enormously important to a variety of optoelectronic applications.

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Y.C. Shih and B.G. Streetman, "Modulation of Carrier Distributions in Delta-Doped Quantum Wells," submitted to Appl. Phys. Lett.

D. List of Scientific Personnel Supported by this Project

1. Ben G. Streetman, Principal Investigator
2. Thomas Block
3. Andrew Campbell
4. B. Chan
5. Yuching Cheung
6. Gentry Crook
7. Susan Foxworth
8. Prabha Kumarakulasingam
9. Thomas Rogers
10. Kayvan Sadra
11. Y-C Shih
12. See-hoi Wong

Degrees awarded

Thomas Block	PhD	expected August 1991
Andrew Campbell	PhD	1989
Gentry Crook	PhD	1989
Susan Foxworth	MS	1990
Thomas Rogers	MS	1989
Y-C. Shih	MS	1991

There were no patents or invention disclosures submitted under this contract.